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Hot Electrons in Liquefied Rare Gases and Electric Breakdown

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Abstract

The paper discusses the problem of the energies of hot electrons as a function of applied electric field strength in lAr, lKr, and lXe and its relation to optical excitation and electrical breakdown.

Introduction

The investigation of electronic conduction in liquefied rare gases is of considerable fundamental and practical interest. The liquefied rare gases represent the most simple class of non-polar dielectric liquids. They are insulators due to their large band gap. Excess charge carriers have to be introduced by external means. The most common methods for the injection of electrons are emission from sharp tips or blades or ionization of the liquid by high-energy radiation, as x-rays or particles. In an applied homogeneous electric field these electrons acquire a drift velocity, v_d the magnitude of which depends on the applied electric field strength. At low field strengths, E, the drift velocity is proportional to the field strength,

$$v_d = \mu E \quad (1)$$

The constant of proportionality is called mobility, μ of the electrons. The electrons carry-out a random path with a component against the direction of the electric field (see Fig. 1). The main interactions of the electrons with the atoms of the liquid are elastic collision, where an amount of energy, $\Delta\varepsilon$, is transfered to the atom on the average,

$$\Delta\varepsilon = \frac{2m_{el}}{M_{at}}\varepsilon = f\varepsilon \quad (2)$$

m_{el} is the electron mass and M_{at} stands for the atomic mass. The ratio $f = 2\ m_{el}/\ M_{at}$ decreases going from helium to xenon (see Table 1). With increase of the electric field strength, electrons pick up more energy from the electric field than they can loose in subsequent

Table 1: Comparison of heat of vaporization and elastic energy loss; A atomic weight, f mean elastic energy loss, ΔH heat of vaporization, ΔE_5 energy loss of a 5 eV electron in an elastic collision. Comparison of optically excited states and ionization energies. Data from references [1, 2].

	A	f	ΔH (meV)	ΔE_5 (meV)	E_{opt} (eV)	I_{liq} (eV)	$I_{liq} - E_{opt}$ (eV)
He	4	$2.7\ 10^{-4}$	0.87	1.35	~16	25.5	~ 9.5
Ne	20	$5.4\ 10^{-5}$	1.79	0.27	~16	21.58	~5.6
Ar	40	$2.7\ 10^{-5}$	67.7	0.135	9.8	14.4	~4.6
Kr	85	$1.3\ 10^{-5}$	94.3	0.065	8.2	11.56	~3.4
Xe	131	$8.3\ 10^{-6}$	131.6	0.041	7.1	9.2	~2

collisions. Their mean energy increases above the thermal energy of the atoms of the liquid, given as k_BT. Electrons in lAr to lXe exhibit a high mobility, which can be described as that of a delocalized electron,

$$\mu_{el} = \frac{e}{m_{el}}\tau \tag{3}$$

Here, τ denotes the relaxation time, or in simple terms, the time between two subsequent collisions. At higher values of the electric field strength, τ decreases with field, μ_{el} becomes inversely proportional to E, finally. Between two subsequent collisions the electron picks up energy from the field given by,

$$\Delta\varepsilon = eE\lambda \tag{4}$$

λ denotes the mean free path between collisions. At the following collision it loses an amount of energy given by Eq. 2. For the heavier rare gases, Ar, Kr, Xe, this energy loss is much smaller than the gain from the field and at a given electric field strength the electron collective aquires a mean energy much greater than k_BT of the liquid. Roughly speaking, the energy increases with applied field as given by Eq. 4. More refined theoretical considerations taking into account various cross sections allow to calculate the dependence of the electron mean energy on electric field strength. Results for lAr (~84K) and lXe (~165K) are summarized in Figures 2 and 3. Once the electron energy reaches values of the optical excitation levels, the electrons lose quanta of energy equal to the optical excitation. After such a collision, the electron energy falls to values around k_BT. If stable conditions in a homogeneous electric field could be achieved, in principle, this condition could be used to create a light source for the far UV. Liquid xenon would be especially promising. Unfortunately, the width of the band of excitation levels is 2 eV , only (see Table 1). Electrons reaching the mean energy of 7.1 eV will have a distribution of energies reaching up to the ionization threshold of 9.2 eV. In addition the high energy photon of 7.1 eV will liberate more electrons from the cathode. Both effects set the conditions of a self-sustaining discharge. This discharge will quickly change into a gas discharge. The ionization rate (first Townsend coefficient) has been estimated for liquid xenon, but the experimental set-up consisted of an electrode arrangement exhibiting a concentric cyclindrical geometry. The anode consisted of a thin wire of 5 μm diameter. By this arrangement the formation of a self-sustaining discharge was inhibited. Similar measurements for lAr were not successful until now.

The results of the theoretical calculation vary considerably from each other. One problem to be solved in the dependence of electron mean energy vs electric field is the measurement of reference points, i.e. excitation of specific energy levels. Measurements at such high field strengths, i.e. >100 kV/cm are difficult to perform since many other factors, as electrode surface, dust particles, cosmic radiation may lead to premature breakdown. Careful experiments with small separation distances of the electrodes, pulsed application of high voltage and pulsed generation of seed electrons may help to overcome the experimental difficulties.

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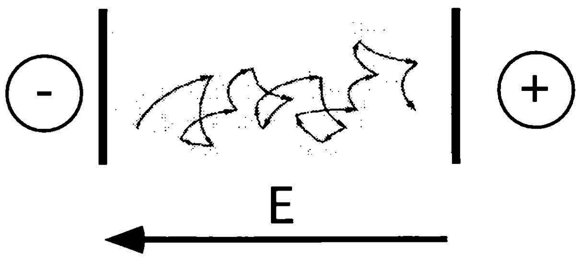

Fig. 1: Random path of an electron in an electric field

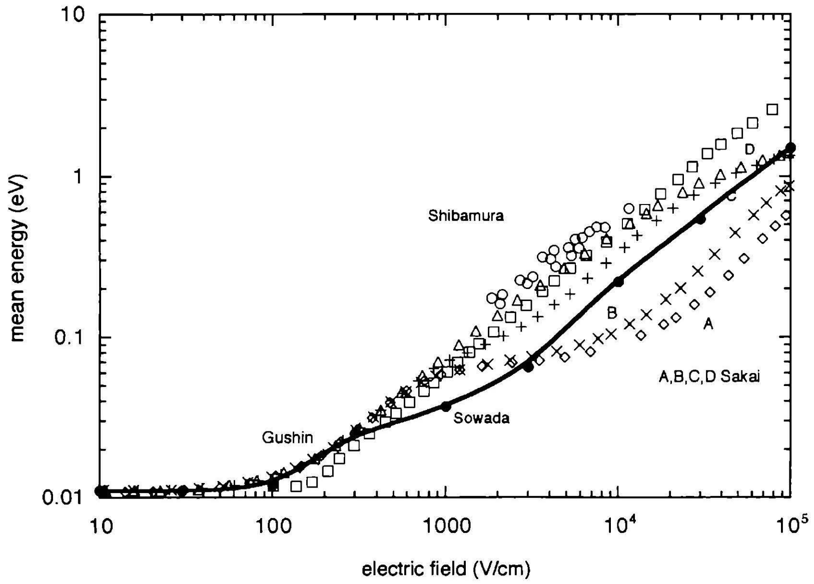

Fig. 2: Electron mean energy as a function of applied electric field in lAr (~84 K). Data from references [3-7]

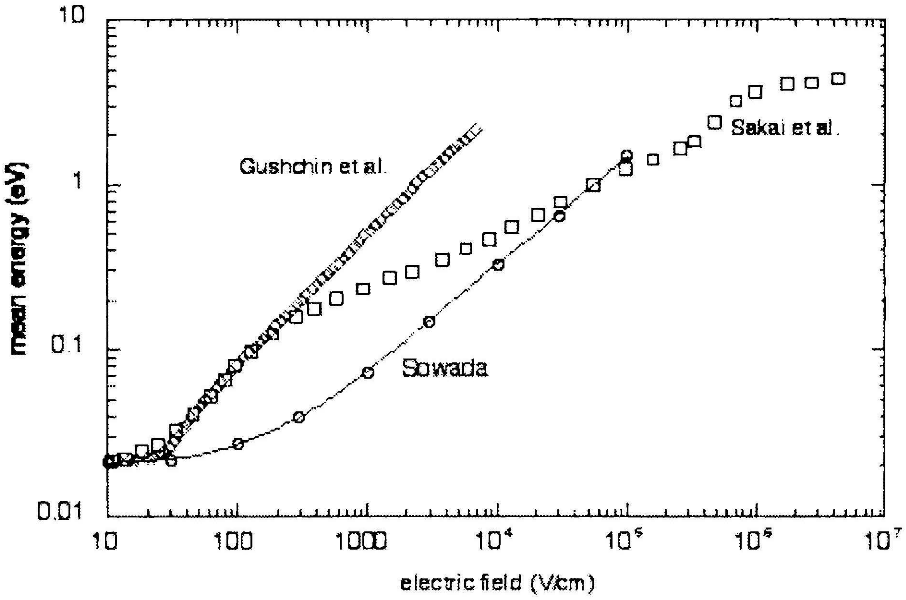

Fig. 3: Electron mean energy as a function of applied electric field in lXe(~165 K). Data from references [3,6,7]